Darwin City Waterfront Redevelopment

HYDROGEOLOGY

Technical Assessment for the
Draft Environmental Impact Statement

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1. Objectives and Scope

The objectives and scope of this technical assessment of the hydrogeology of the Darwin Waterfront Redevelopment area comprise:

- Assess and describe the existing hydrogeology and groundwater conditions under the proposed redevelopment and in the nearby area, including the potential for contaminated groundwater to move off proposed redevelopment;
- Identify features of the proposed development that may impact on the groundwater under and in proximity to the proposed redevelopment; and
- Identify measures that will minimise any adverse impact and/or enhance any positive impact on the hydrogeologic environment and groundwater under and near the proposed redevelopment.

2. Description of the existing environment

2.1 Previous Groundwater-Related Studies

2.1.1 Shell Bitumen Plant

- Groundwater Technology of Australia Pty Ltd - Environmental Proposed redevelopment Assessment Report, Shell Bitumen Plant, 3 February 1995 (A4049B)

Groundwater Technology of Australia (GTI) undertook an investigation at the Shell Bitumen Plant proposed redevelopment to determine the nature and extent of hydrocarbon contamination as a result of hydrocarbon storage and proposed redevelopment activities. The scope of works included the drilling of 17 soil bores (0.5 to 7.0 m deep), seven groundwater monitoring wells; soil and groundwater sampling and analysis, and estimation of soil permeability and groundwater flow characteristics.

The investigation is reported to have encountered micaceous gravely clay and silt overlying siltstone bedrock at shallow depths with several holes terminated upon refusal. Groundwater occurred at depths of about 4 meters below ground level with groundwater flow to the southeast. Groundwater analysis identified elevated concentrations of TPH in the southern part of the proposed redevelopment.

- IT Environmental - Environmental Proposed redevelopment Assessment Report, October 1999 (J409489A)

IT Environmental undertook a second ESA at the Shell Bitumen Plant proposed redevelopment to delineate the extent of hydrocarbon impact that may have occurred at the Bitumen Plant as a result of hydrocarbon storage and proposed redevelopment activities and to assess trends in groundwater. Five soil bores were drilled and converted to groundwater monitoring wells.

- IT Environmental - Environmental Proposed redevelopment Assessment Report, October 1999 (J409489A)

Groundwater levels beneath the proposed redevelopment ranged from 3.5 to 4.0 mbgl. PSH of 0.02 m was detected in one GMW. Groundwater flow direction to south southwest.

- IT Environmental - Environmental Proposed redevelopment Assessment Report, October 1999 (J409489A).

Groundwater field monitoring field results were: pH of 5.9 to 6.6; TDS of 74 to 11,461 mg/L; and dissolved oxygen of 0.39 to 1.8 mg/L. No BTEX or PAHs at concentrations above the LOR in any sample. Lead was reported in one groundwater sample at a concentration of 1 μg/L. TPH was detected in 5 GMWs. A dissolved offproposed redevelopment petroleum hydrocarbon plume exists to the southeast of the proposed redevelopment with a further plume located to the northwest.

- IT Environmental - Groundwater Monitoring Event (GME), November 2002 (J409489D)

A GME was undertaken at the Shell Bitumen Plant proposed redevelopment to identify trends in groundwater elevation, water quality parameters and hydrocarbon concentrations as part of the ongoing monitoring at the proposed redevelopment.

Fieldwork included groundwater gauging, purging, sampling and measuring of water quality parameters in four monitoring wells.

The groundwater flow direction is towards the south-southeast to south-southwest. A possible large diurnal fluctuation in groundwater level, due to the proximity of the proposed redevelopment to the ocean. The hydraulic gradient beneath the proposed redevelopment was reported to be 0.001.

BTEX concentrations reported during this GME were reported to be less than the laboratory LOR in all wells. All TPH-impacted wells are located to the southeast of the proposed redevelopment.

- Geotechnical Review of Shell Reports

A total number of 22 shallow boreholes were drilled and 12 monitoring well installed within and close to the Bitumen plant in 1995 and 1999 by Ground Water Technology Australia and IT Environmental respectively.

Subsurface condition at the bitumen plant proposed redevelopment comprised p layer of gravelly clayey silt (fill) overlying weathered siltstone (phyllite) at 0.5m to greater than the total investigation depth of 7.0m below the ground surface. Plastic and wood debris were encountered within the gravely clayey soil layer in some boreholes. In addition, some boreholes encountered drilling refusal close to the shallow ground surface and interpreted as concrete or building rubble within the fill material. The fill material is probably material such as metal pipes and concrete debris.

The groundwater level was 3.5m to 4.0 mbgs. The ground water level is likely to be influenced by the daily tidal fluctuations.

2.1.2 Fort Hill Area

- Dames & Moore (1984). Soil Investigation – Darwin Ro-Ro Mooring.

Two shallow auger boreholes were drilled between the Iron Ore Wharf and Fort Hill Wharf (Dames & Moore, 1984) as part of the investigation for the Ro-Ro mooring. The investigation revealed a surficial 0.2 to 1.0 m thick layer of marine mud overlying weathered phyllite. The less weathered phyllite was inferred (from refusal of auger drilling) at 0.55 m and 1.75 m below the seabed.

2.1.3 Warehouse Area

- Coffey & Hollingsworth – Geotechnical Investigation for Port of Darwin Development Vol VF Kitchener Drive. 1970
- Coffey & Hollingsworth – Geotechnical Investigation for Port of Darwin Development Vol VI Fort Hill. 1970

Geotechnical data available for the Warehouse area are limited to 6 boreholes completed in 1970 as part of a geotechnical investigation for Shed 2. The subsurface conditions across the footprint of Shed 2 proposed redevelopment comprised three distinct units; loose phyllite fill (5.2 m to 7.6 m thick) overlying marine mud (1.1 m to 7.6 m thick) and phyllite bedrock (grading from highly weathered to slightly weathered).

Phyllite fill borrowed from the Stoke Hill area during early 1969 was used to reclaim the proposed redevelopment. The depth of fill ranged from 5.2 m to 7.6 m. The phyllite at the borrow area was described as a soft friable rock comprising fine-grained quartz, mica and clay. Underlying the fill is a layer of marine mud ranging in thickness from 1.1 m to 27.6 m thick.

Below the soft mud was a layer of extremely weathered phyllite, 5.5 to 13 ft thick, described as partly gravel-size particles in a clay matrix.

2.1.4 Recent Reclaimed Area

- Dames & Moore – Proposed redevelopment Investigation Kitchener Bay Supply Base 1989

The mud comprises clay/silty clay overlying a thin layer of silty sand before grading to a sandy clay. Mud depths, seawards of the two Sheds, are greater than 7.2 m and approximately 5.5 m, close to the Fort Hill Wharf approach;

The composition and depth of fill material used at the Recent Land Reclamation Area is unknown. Anecdotal evidence suggests that, until 10 years ago, the area was extensively used by the Port Authority as a general refuse landfill. The likely composition of the fill may be a mixture of soil, rock, and general industrial and building waste.

2.1.5 Old Northern Cement Area

There is no formal record of the nature and thickness of fill material at the former Northern Cement Plant Area. However, a borehole drilled by GTI in 1994 approximately 10 m northwest of the North Cement Plant Area intersected 4.5 m thick layer of fill, overlying soft clayey silt (marine mud). The fill comprised silty clayey gravel with concrete and wood fragments.

2.1.6 Stokes Hill Tank Farm

- Acer Vaughan (1992). Wharf Precinct - Assessment of suitability of Rock Fill Material from Stokes Hill Wharf.

Original hill comprised flat lying porcellanite caprock overlying steeply bedded/foliated phyllite. The porcellanite described as claystone/siltstone that has been laterised and hardened to a durable rock.

Phyllite describes a micaceous metamorphosed siltstone, which unconformably underlies the Bathurst Island Formation. The phyllite is described as a generally weak foliated rock. Faults in the phyllite are usually filled with quartz.

2.1.7 Recent URS Groundwater Studies and Field Programs

During late 2003 and early 2004, 25 groundwater monitoring wells (GMWs) were installed across the development proposed redevelopment as part of the Phase 2 DCA (**Table 3.1**). The GMWs were constructed with a 50 mm diameter Class 18 PVC casing and constructed with a sealed and gravel packed basal slotted section (6 to 7 m long) with an end cap.

The geology over the screened interval for each of the GMWs installed by URS at the proposed redevelopment can be characterised as either bedrock or marine sediments (**Table 3.1**).

Table GW1 Summary of Drilling

Investigation		Phase 2 DCA		FGI
Area	Depth Range (m)	Groundwater Monitoring Wells (monitored interval lithology	Soil Boreholes	Boreholes
Fort Hill Area	0.75 - 15.0	5 (4 marine seds, 1 bedrock)	29	6
Bitumen Plant Area	5.5 - 18.5	0	2	2
Warehouse Area	3.0 - 21.0	1 (marine seds.)	16	11
Old Northern Cement Plant Area	22.5	1 (marine seds.)	0	1
Recent Reclamation Area	11.0 - 21.0	4 (marine seds.)	5	9
Stokes Hill Area	1.3 – 20.0	9 (6 bedrock, 3 marine seds.)	11	7
Kitchener Drive	6 – 10	5 (4 bedrock, 1 marine seds.)	0	1
Total	**0.75 -22.5**	**25**	**64**	**37**

2.1.8 Groundwater Well Sampling

Upon completion of installation, all 25 groundwater monitoring wells installed by URS were developed, purged, tested and sampled according to URS QA/QC protocols, which comply with NEPM Guidelines.

All bores were purged and sampled. Groundwater parameters were tested from each bore volume purged including electrical conductivity (EC), pH and dissolved oxygen (DO). During sampling, the following parameters were recorded: standing water level, bore volume, method of purging and sampling, volume of groundwater purged, water quality parameters, colour, turbidity odour and presence of hydrocarbons

2.1.9 Groundwater Tidal Monitoring

Monitoring of water levels in 11 selected GMWs was undertaken over approximately 13 hours on 13 and 14 December 2003. The monitored GMWs were considered representative of conditions across the proposed redevelopment and included GMWs screened in either rock (phyllite or porcellanite) or fill/marine sediments. Locations were also selected based on their proximity to the ocean.

2.2 Proposed Redevelopment Geology

The 1:100,000 scale 'Darwin' (1983) Geological Survey of Northern Territory Map (Sheet No. 5073), indicates that the geology underlying the development generally comprises:

- Quaternary sediments along the foreshore consisting of mud, clays, silts, intertidal marine alluvium; underlain by;
- Bathurst Island Formation sediments of the Lower Cretaceous Period, comprising radiolarian claystone; sandy claystone; clayey sandstone; quartz-sandstone; ferruginous sandstone; glauconitic sandstone, underlain by;
- Burrell Creek Formation of the Finniss River Group, comprising siltstone; shale; sandstone (quartz arenite, sublitharenite); quartz pebbles conglomerate; metamorphosed to lower greenschist facies (referred to below as phyllite).

Based on recent URS field investigations (URS, 2003) three general types of subsurface materials occur under the development proposed redevelopment - fill, marine sediments ("mud") and phyllite bedrock. The composition and likely geotechnical properties of these materials are summarised in **Table 3.2**.

Table GW2 Description of Subsurface Materials

Material Type	Composition	Geotechnical Characteristics
Fill	Phyllite soil and rock	Have been used as non structural fill
	Phyllite soil and rock with debris (building, domestic and industrial waste)	Heterogeneous, may be subject to collapse when metal debris corrodes.
Marine Mud	Sandy clay Sandy silt	Very soft at surface with some increase in strength with depth
Phyllite	Weathered	Extremely weak, can be friable and broken with finger pressure Behaves like silt when remolded or mechanically disturbed Extremely low CBR when soaked in water
	Less weathered	More competent, but generally classified as a weak rock.

The subsurface soil profile across the reclaimed Kitchener Bay Areas (Warehouse Area and Recent Reclaimed Area) comprises a surficial layer of fill overlying: (i) bedrock in areas close to Kitchener Drive; and (ii) marine mud seaward of the two Sheds. Underlying the marine mud, a layer of extremely weathered phyllite bedrock (grading to less weathered with depth) occurs. The fill material (ranging up to 7 m thick) is mainly phyllite with concrete/construction debris and general industrial waste.

The subsurface profile from Kitchener Drive to seaward of the Fort Hill Areas comprises a layer of fill overlying part of the original cut Fort Hill bedrock. Areas closer to the existing wharfs are underlain by thicker fill. Similarly, the subsurface conditions at the former Power Station Area probably comprise fill material overlying the original Stokes Hill bedrock. Areas closer to the shoreline have more fill materials. The thickness of the fill under the Fort Hill and Power Station areas is generally unknown.

2.3 Groundwater Geology and Hydrogeological Setting

Groundwater under the Darwin CBD is typically encountered in low permeability, fractured bedrock aquifers of the Burrell Creek Formation, with typical bore yields of 0.5 – 5.0 L/s. Groundwater levels vary seasonally by 10 to 15 m.

The proposed development is located below the bedrock scarp that marks the south-eastern boundary of the CBD and is largely reclaimed land (fill) overlying low permeability marine sediments (mainly mud) and weathered to fresh bedrock. It is doubtful whether any significant aquifers occur in these sediments or the underlying bedrock. Near the coast the groundwater level under this low-lying area is more or less equal to mean sea level. Inland towards the bedrock scarp, groundwater elevations increase – resulting in a generally southeasterly groundwater flow under the proposed development.

Assuming a very low permeability of the lithological materials under the proposed development, the groundwater and soil contamination under the area, resulting from previous land uses, must move very slowly towards the marine environment.

2.4 Groundwater Levels and Movement

Due to the proximity of the proposed redevelopment to the sea, the depth to groundwater is shallow and the direction of groundwater flow is generally towards Darwin Harbour. Anecdotal information suggests that during the wet season (high groundwater elevations), groundwater discharges from the bedrock scarp to the northwest of the wharf facility.

In order to determine groundwater movement under the proposed redevelopment, groundwater elevations were determined for recent GMWs (Figure 7). The inferred groundwater contours indicate that the maximum groundwater elevation at the proposed redevelopment was approximately 5.0 m AHD in a groundwater mound beneath Stokes Hill. Another groundwater mound (to approximately 3.0 m AHD) occurs beneath Fort Hill. Radial groundwater flow occurs away from these mounds towards the coast.

Groundwater elevations along Kitchener Drive vary by over 2m, with a groundwater mound along the toe of the escarpment along the northern portion of the drive. Along the southern portion of the drive, there is a gradient reversal and flow occurs towards the bedrock scarp, possibly due to drainage effects from the nearby World War II storage tunnels.

Ground throughflow under the proposed redevelopment (F**igure 3.3**) can be estimated using Darcy's Law as

$$Q = K\ i\ A$$

Where, K = permeability (m/day); (a range of assumed values have been used);

i = hydraulic gradient; (average taken from Figure 7);

A = cross-sectional area of flow (m^2); (perimeter 2,400 m, varying flow depths assumed).

Table GW3 Calculated Groundwater Throughflow Under Proposed Redevelopment

Average Permeability of Flow Section (m/day)	Average Hydraulic Gradient	Assumed Cross-Sectional Flow Area (perimeter times depth - m^2)	Calculated Throughflow (m^3/day)
0.005	0.001	2400 m x 10 m	0.1
0.005	0.005	2400 m x 20 m	1
0.005	0.01	2400 m x 30 m	4
0.01	0.001	2400 m x 10 m	0.2
0.01	0.005	2400 m x 20 m	2
0.01	0.01	2400 m x 30 m	7
0.05	0.001	2400 m x 10 m	1
0.05	0.005	2400 m x 20 m	12
0.05	0.01	2400 m x 30 m	36
0.1	0.001	2400 m x 10 m	2
0.1	0.005	2400 m x 20 m	24
0.1	0.01	2400 m x 30 m	72

Based on these results, the groundwater throughflow under the proposed redevelopment is probably less than 10 m^3/day. This may be advantageous, given the amount of groundwater contamination under the proposed redevelopment.

2.4.1 Tidal Efficiency

Tidal fluctuations influence groundwater levels in aquifers that occur near the coast. However, the tidal influence on confined or unconfined aquifers differs.

Groundwater levels in confined aquifers (groundwater under pressure) respond during tidal fluctuations due to changes in hydraulic loading (caused by the weight of overlying seawater) acting downwards on the confining bed above the aquifer. For example, at high tide the extra weight of seawater will cause groundwater levels in the aquifer to rise.

In unconfined aquifers (groundwater at atmospheric pressure), tidal fluctuations cause changes in groundwater levels as the seawater enters or leaves that portion of the aquifer which outcrops or subcrops along the coast. Thus, a high tide next to an unconfined aquifer will also cause rising groundwater levels, but this will be a result of seawater entering that portion of the aquifer in close proximity to the coast.

The tidal influence on unconfined aquifers is much less than that on confined aquifers, mainly because of larger storativity in unconfined aquifers resulting in a groundwater level response time that is generally much slower than the tidal changes.

The tidal efficiency of an aquifer is the ratio of the change in groundwater level to the corresponding change in tide level. In confined aquifers, tidal efficiency is a measure of the incompetence of the overlying confining bed to resist pressure (loading) changes. Groundwater level change resulting from tidal changes decreases inland. The time taken for the maximum tide to result in a maximum groundwater level increases inland.

Table 3.4 summarises the interpretation of the results to assess the tidal influence and tidal efficiency of the different lithological types at the proposed redevelopment.

Table GW4 Results of Tidal Influence Monitoring

Monitoring Bore	Depth	Screened Lithology	Time Lag – Rising Tide to Rising GWL(hours)	Distance From Coast (m)	Tidal Efficiency (%)
KD_MW06	7	Bedrock	NDR	292	NDR
SH_MW08	10.3	Bedrock	1*	208	1*
FH_MW21	10.2	Bedrock	1.5*	156	2*
SH_MW23	10	Bedrock	4.5*	80	1*
WA_MW07	10	Marine Sediments	NDR	200	NDR
SH_MW10	9	Marine Sediments	2.5	28	30
SH_MW12	15	Marine Sediments	NDR	140	NDR
RR_MW13	10	Marine Sediments	4	40	42
RR_MW15	10	Marine Sediments	<1	132	11
NC_MW17	10	Marine Sediments	<1*	44	2*
FH_MW19	10	Marine Sediments	3.25	40	70

Note: NDR: No discernible groundwater level response to tidal changes**;** * groundwater level fluctuation may not be caused by tidal influence.

The results summarised in **Table 3.4** indicate the following:

- Groundwater levels in bedrock monitoring bores show little, if any, influence from tidal fluctuations, regardless of distance from the coast. Therefore any groundwater contamination in these rocks can not be affected by groundwater movement caused by tidal fluctuations;

- Groundwater levels in marine sediment monitoring bores show significantly more influence by tidal fluctuations. Bores within 50 m of the coast show tidal efficiencies ranging up to 70%, although the tidal efficiency does not appear to be related to distance from the coast. Further inland than 50 m, tidal efficiency rapidly declines and there is no detectable tidal influence greater than 150 m from the coast. There is no inverse relationship between distance from the coast and tidal efficiency, as would have been expected.
- The time lag between rising tidal level and rising groundwater level is highly variable and does not appear to be related to distance from the coast. This is to be expected in the bedrock due to the anisotropic distribution of permeability. However, in the marine sediments this may indicate a significant variation in lithology locally.
- The range in tidal efficiency suggests that the aquifer zones present under the project proposed redevelopment are both confined and unconfined. They are probably confined under the ocean where they extend offshore but may also receive some tidal effects through water movement into and out of the steep beach line at the coast. Aquifer zones in the bedrock are confined but are generally too far from the coast to be influenced by tidal fluctuations.
- Based on the above findings, it is difficult to understand how tides can exert significant impacts on any groundwater contamination under the proposed redevelopment. In most cases at the proposed redevelopment, the tidal influence does not represent a movement of seawater into and out of the aquifer, rather a change in loading. Along the steep beach line, some movement of seawater into and out of the marine sediments may be occurring, but these sediments have such a low permeability that very little movement of contaminated groundwater can take place.

2.5 Hydraulic Parameters

Very, little is known about the hydraulic parameters of the lithological materials under the proposed development, due to the general lack of field testing for these parameters.

Field permeability testing by GTI indicated a vertical infiltration rate of 1.5 cm/hr and an aquifer hydraulic conductivity (permeability) of 0.04 m/day from slug testing.

Based on the lithology of both the fill and the marine sediments, the permeability of these strata must be very small. Similarly, the phyllite bedrock has no intergranular permeability and groundwater flow is restricted to secondary structures such as faults and joints.

2.6 Groundwater Chemistry and Contamination

Groundwater in the area of the proposed development is typically fresh to saline (<1,000 to 40,000^{+} mg/L TDS), generally depending on distance from the coast and the lithology of the monitored interval in the GMW. Groundwater in the bedrock near the scarp and in groundwater mounds is generally less than 1,000 mg/L. Groundwater in the marine sediments near the coast has TDS contents of 20,000 to 40,000 mg/L. All groundwater is a Na-Cl type with varying amounts of Mg, Ca and sulphate.

Groundwater in the bedrock underlying the Darwin area is typically of low salinity (500 – 1,500 mg/L TDS) and is generally suitable for human consumption and irrigation.

The areas and types of groundwater contamination under the proposed development are listed below:

- **Fort Hill Area** – elevated (compared to guidelines) Cu, Mn, Zn and TPH concentrations;
- **Bitumen Plant Area** – no groundwater sampling, but soil has elevated concentrations of As, Cd, Cu, Mn, Pb and Zn;
- **Warehouse Area** – one GMW that indicated elevated concentrations of TPH, PAHs, phenols and Cu. In this area, the groundwater is probably as impacted as the soil, but only one GMW exists.
- **Old Northern Cement Plant Area** – elevated concentrations of Mn, Zn and ammonia.

- **Recent Land Reclamation Area** – elevated concentrations of Mn and Zn, but these may be naturally elevated compared to guidelines.
- **Stokes Hill Area** – various hydrocarbons with elevated concentrations at depths greater than 3 m and presumed moving with the groundwater flow, also elevated concentrations of Cu, Mn, Pb, Zn and ammonia.
- **Kitchner Drive Fuel Pipelines and WW II Storage Area** – hydrocarbons present in the groundwater, assumed source is pipelines.
- **Marine Sediments** – elevated concentrations of As, Cd, Pb and Zn, in excess of guidelines in the Fort Hill Area.

There has not been enough groundwater sampling and analyses to determine the natural background concentrations of the various metals listed above. While they are present in concentrations above various guideline values, this is possibly a natural occurrence due to the geochemistry of the various geologic strata present and may not represent groundwater contamination. This needs further investigation.

3. Description of the proposed development

Groundwater-related concerns about the proposed redevelopment include:

- A lack of hydrogeological knowledge of the site, including the occurrence of aquifer zones;
- Current inability to quantify groundwater contamination, both vertically and horizontally, under the site;
- The presence of PASS;
- The shallow water table under the site;
- The design of surface runoff and storm water infrastructure for the proposed redevelopment;
- The relationship between the groundwater in the marine sediments and the underlying bedrock;
- Determining whether groundwater contamination is still occurring;
- The best method to reduce groundwater contamination; and
- Determining the effect of the discharge of contaminated groundwater from the site on the marine environment.

4. Assessment of potential impacts from the proposed development

4.1 Disturbance of Acid Sulphate Soils

Acid sulphate soil materials (ASS) are naturally occurring materials that soils are saline soils or sediments containing a build-up of iron sulphides (pyrite) under waterlogged or highly reducing conditions (i.e. sulphidic conditions). These conditions are often characteristic of low-lying coastal areas, which are ideal for acid sulphate soil formation.

In the natural setting these layers are covered by soil and are beneath the local water table. In this state, the potential acid generation is held within the soil (as sulphide minerals). When the acid sulphate soils are exposed to the atmosphere, either directly by removal of the covering soil layers or by the lowering of the local water table (eg. through drainage or dewatering activities), then oxidation of the iron pyrite occurs resulting in the formation of sulphuric acid.

Problems arise when the rate of acid production from oxidation of sulphides exceeds the buffering capacity of the soil. This affects water acidity reducing pH to as low as 2,which results in the leaching of iron, aluminium and other trace metals from the local soils into waterways and groundwater, sometimes at levels toxic to aquatic organisms. Development of ASS in the root zone of most plants causes loss of productivity and acid runoff causes adverse impacts to environment, coastal development, fishing, and agricultural and mining industries.

The coastal location of the Darwin Port Development prior to infilling was characteristic of proposed redevelopments where ASS actively formed. The process of ASS formation occurs in an anaerobic environment when sulphate rich seawaters mix with terrestrial sediments containing iron oxides and organic material (Powell and Ahern, 2000). The breakdown of organic material (plant and animal) takes place in an oxygen-depleted environment (reduced conditions) in the presence of activating obligate sulphur-reducing anaerobic bacteria (*Desulphouibrio* and *Desulphotomaculum genera*). This accelerates the decomposition and utilisation of the abundant supply of sulphates from seawater for their respiratory processes, thus producing sulphides.

4.2 Movement of Groundwater Contamination

Previous studies by URS and others have shown that areas of contaminated groundwater occur under the proposed redevelopment. Based on groundwater elevations, the general movement of groundwater under the proposed redevelopment is towards the ocean. However, based on aquifer parameters and simplistic calculations, the movement of groundwater (and therefore groundwater contaminants) towards the ocean is very slow.

Many of the metals and hydrocarbons found in the groundwater and soils are hazardous to the environment and humans. Their presence may delay work in the area due to the amount of handling and contamination removal that could be required. The development may cause further groundwater contamination by the movement of soils and groundwater around the proposed redevelopment and by dewatering operations. Thus construction activities must be carefully planned, because the full extent of groundwater contamination under the proposed redevelopment is not yet properly known and further groundwater studies are required prior to the commencement of construction.

4.3 Groundwater Pumping or Discharge

It is probable that groundwater pumping and drainage will be required for local dewatering associated with foundation placement and other infrastructure. This groundwater may require treatment prior to disposal and the lowered groundwater level associated with dewatering and drainage may cause groundwater contamination plumes to change flow direction. This may have the effect of spreading the distribution of groundwater contamination under the proposed redevelopment.

Near the coast, such groundwater pumping or discharge may cause seawater intrusion into the strata under the proposed redevelopment.

The activation of PASS is also associated with groundwater level lowering.

4.4 Increased Groundwater Recharge

Depending on drainage and stormwater designs, the proposed development may increase recharge to groundwater from surface runoff and cause the water table to rise. Such a rise may result in water-logging of low-lying areas of the development with the associated environmental problems.

Construction design should be considered in this matter.

5. Mitigation strategies

5.1 Additional Studies

Suggested additional work that is required prior to the commencement of the development comprises:

- Groundwater flow and solute transport modelling to predict contamination movement and assist in remediation planning;
- Further quantification of soil and groundwater contamination under the proposed redevelopment;

- Additional hydrogeological studies of the proposed redevelopment to better understand groundwater movement under the proposed redevelopment and establish the relationship between groundwater and sea water;
- Complete quantification estimates of the amount of groundwater contamination reporting to the marine environment; and
- Determine the presence of significant aquifer zones in both the marine sediments and the underlying bedrock.

5.2 Groundwater Monitoring Network

Additional GMWs will be required in the future to create a more widely distributed groundwater-monitoring network. This will allow a more complete understanding of the distribution (both vertically and horizontally) of groundwater contamination and therefore the most appropriate remediation strategies.

Although it is felt that tidal influence will not affect the distribution of groundwater contamination, groundwater level fluctuations and tidal fluctuations should be compared semi-annually to confirm or otherwise the calculated tidal efficiencies outlined in this report.

5.3 Groundwater Monitoring Programs

A regular program of groundwater level monitoring and groundwater sampling and analysis from the GMWs on the proposed redevelopment is required. These data will help to form the conceptual hydrogeological model of the proposed redevelopment and thus assist in a number of groundwater-related matters, including quantification and movement of groundwater and groundwater contamination.

It is suggested that a groundwater monitoring program is designed to enhance the hydrogeological knowledge of the proposed redevelopment.

5.4 Acid Sulphate Soils and Infrastructure Protection

The disturbance of acid sulphate soils needs to be carefully managed. Some of the more obvious concerns include:

- If such soils are stockpiled during construction, they will need to treated with lime and encapsulated as much as practical to stop the generation of acid runoff and the associated groundwater contamination with heavy metals.
- Lowering of the water table could expose acid sulphate soils to atmospheric oxygen and acidify groundwater to a low pH. This in turn will dissolve and mobilise heavy metals, probably towards the marine environment. Therefore, any dewatering that is required for foundation placement should be done as quickly as possible and the dewatering discharge sampled and analysed on a regular basis to determine the initial baseline groundwater chemistry and any changes in groundwater chemistry during dewatering. If groundwater pH starts to decrease significantly, then a suite of metals will also need to be analysed. The ultimate end product of this process would be the requirement to treat and remove the dewatering discharge from proposed redevelopment, rather than disposing of it into the ocean.
- All foundations, including piles, need to be designed with materials that are resistant to acid soils and the associated corrosion. For example, sulphate-resistant cement may be required in some or all of the development areas. Piles may require treatment with chemicals that are resistant to the potential acidification of soils and groundwater.
- Revegetation of the development area may need to take account of soil types and the potential for acid sulphate soils to generate acid in the subsurface. Lime treatment of soils is one obvious treatment, but presumably there are also other suitable treatment methods.

5.5 Groundwater Contamination

With further groundwater studies, the extent and distribution of groundwater contamination will better known. There will be a number of alternatives to remove and deal with this contamination, including natural attenuation, pump and treat, and permeable reactive barriers.

The remediation of groundwater contamination may be very costly, but may be necessary for environmental and health reasons. Natural attenuation is a walk away solution, provided that the amount of groundwater contamination entering the marine environment can be quantified and the effects determined.

5.6 Rising Water Table Due to Increased Recharge

A rising water table and groundwater levels may have negative aspects on the development and may need to be controlled by drains and or groundwater pumping. It is suggested that the design of all developments within the area should consider the removal and methodology for handling surface runoff and stormwater drainage. With proper design (ie not disposing of this water into soak wells), this potential problem will probably not occur and should be avoided as it may result in a number of detrimental effects on the developments.

5.7 Saltwater Intrusion

It may be disadvantageous for the sea water–groundwater interface to move inland from the coast into strata under the proposed redevelopment, including the bedrock. This could be caused by excessive groundwater pumping under the proposed redevelopment or from the underlying bedrock. In the latter case, aquifers under Darwin could be affected if such intrusion occurs large distances inland and this has the potential to influence existing groundwater users. The low permeability of the strata should theoretically prevent this occurrence, however the occurrence and distribution of aquifer zones under the proposed redevelopment are currently not known.